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A CRITICAL COMPARISON OF REMOTE SENSING AND OTHER METHODS FOR NONDESTRUCTIVE ESTIMATION OF STANDING CROP BIOMASS*

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ABSTRACT

Several different techniques for the nondestructive estimation of pasture or range biomass are critically reviewed and compared to remote sensing methods. Similarities and differences between the visual estimation procedure, β-attentuation, capacitance meters, weighted disc, and spectral methods are discussed in terms of accuracy, time, ease of operation, operational constraints, and calibration procedures. No one technique has been shown to be superior across the board to the other techniques reviewed for ground-based biomass estimation. A discussion of the strengths and weaknesses of each nondestructive method allows for the selection of the technique most suited to a particular application.

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INTRODUCTION

Grassland scientists and others involved in the estimation of standing crop biomass have continually attempted to improve upon existing procedures for estimating herbage biomass accurately, inexpensively, and quickly. The traditional methods most commonly used involve the hand clipping of a known area of vegetation and weighing of the resulting sample. The usefulness of clipping as a sampling method is limited by two characteristics: it is a slow, tedious, and time-consuming operation; and it is a destructive sampling procedure which precludes sampling the plot on a repetitive basis.

Several nondestructive biomass estimation techniques have been proposed. Among them are the visual estimation method, weighted disk, capacitance meters, β-attenuation, and remote sensing (spectral) methods.

OPERATIONAL CONSIDERATIONS

Nondestructive methods for estimating herbaceous biomass should meet several criteria. They must be accurate, fast, require a minimum of calibration, and they should be relatively unaffected by environmental circumstances such as mist, dew, wind, clouds, varying irradiational conditions, uneven microtopography, and the like. The instrument(s) used should be light, sturdy, easy to carry, reliable, and inexpensive.

It is doubtful if any one technique will meet all the desired criteria. The extent to which any technique does not meet these criteria can then be compared to the existing methods, which generally involve clipping and as Bryant et al. (1971) observed, "The limitations of these (conventional pasture measurement techniques) need no emphasis."

VISUAL ESTIMATION PROCEDURE

The most commonly used nondestructive technique for estimating standing crop biomass is the visual estimation procedure (Pechanec and Pickford, 1937). The visual method of biomass estimation simply consists of visual observations of several permanent and sacrifice plots by a trained observer as proposed by Wilm et al. (1944). The sacrifice plots are clipped and weighed to develop the regression relationship needed to correct estimates of standing crop biomass on the permanent plots. The equipment needed to conduct this type of inventory includes a pair of shears, plot marking materials, a small scale, and some paper sacks in which to store the herbage clipped. Additional work on this technique has been reported by Morley et al. (1964), Hutchinson et al. (1972), Campbell and Arnold (1973), and Haydock and Shaw (1975).

The visual method of biomass estimation is satisfactory for general grassland inventories, but it suffers from variations among observers and is not quantitative nor accurate enough for many experimental purposes where quantitative biomass data is required. Specialized grassland inventories, however, require more accurate techniques.

β-ATTENUATION

Teare et al. (1966) reported using radioisotopes to determine herbaceous biomass. This technique relies on the absorption or attenuation of β-particles by herbage material which is a predictable function of the density of absorbing herbage in mg cm^{-2}. β-particles have been used for some time in industry as a measure of thickness (Libby, 1961).

The absorption of β-particles by a given material depends to a very large degree upon the interaction of β-particles with the electrons of the absorbing material. The efficiency of an absorber composed of low atomic number elements will be closely proportional to the absorber's density. Absorption by a given thickness (mg cm^{-2}) of material will be practically independent of the atomic number and atomic structure of the material. Since plant material contains a very small proportion of heavy elements, the estimation of plant material density by β-particle attenuation between a radioactive source and detector will give a reliable estimate of herbage biomass (Teare et al., 1966). The radioactive source and detector must be maintained at a constant geometry however, to prevent extraneous sources of variability from being introduced.

Herbage density data can be converted to herbage biomass by integrating the density over the height of the stand. Teare et al. (1966) reported that the problem of estimating herbage biomass in situ with β-attenuation becomes the problem of estimating vegetation density with height.

Mitchell (1972) constructed a makeshift prototype β-attenuation device for shortgrass prairie biomass estimations. He concluded that the β-attenuation method accounted for 90% of the biomass variation measured in the field, with the exception of quadrats dominated by cacti. The β-attenuation biomass estimation was reported to be accurate, precise, relatively inexpensive, and nondestructive. However, the technique was reported to be of limited use on moderately to heavily grazed pastures and microtopographical variations, such as small mounds, were found to be a significant source of error.

In addition to herbage biomass estimation, β-attenuation has been adopted to measuring changes in water content of leaves. This procedure necessitates placing the leaf between a weak β-emitter (C^{14}) and a thin-window Geiger-Muller tube (Mederski, 1961).

CAPACITANCE METERS

Fletcher and Robinson (1956) first reported on the development of an electronic device for measuring the capacitance between or among several probes which had been inserted into the vegetation canopy. The capacitance measured is proportional to the amount of water present in the vegetation. The operating principle is the significant difference between the dielectric constant for

air (!) and that of water present in the vegetation (80). A variety of capacitance meters have been built capitalizing upon this principle and incorporating various modifications (Campbell et al., 1962; Hyde and Lawrence, 1964; Alcock, 1964; Johns et al., 1965; Neal and Neal, 1965; Dowling et al., 1965, Morse, 1967; Van Dyne et al., 1968; Kreil and Matschke, 1968; Jones and Haydock, 1970; Johns, 1972).

The various capacitance meters previously mentioned have been extensively field tested with mixed results. Several workers have reported promising results using these devices (Campbell et al., 1962; Johns and Watkins, 1965; Alcock and Lovett, 1967; Back, 1968; Van Dyne et al., 1968; Back et al., 1969; Johns, 1972; Currie et al., 1973; Neal and Neal, 1973) while others have found that there are too many sources of error which prohibit successful field usage of these devices in many field situations (Bryant et al., 1971).

Advantages of capacitance meters include the linear relationship between capacitance and water present in the herbaceous vegetation, general rapidity with which measurements can be made, and the simplicity of use. Disadvantages include the impossibility of wet-weather operation, the adverse effect of water droplets or dew upon the readings, frequent need for recalibration, and the need to operate on homogeneous herbaceous canopies of similar phenology.

WEIGHTED DISC TECHNIQUE

Jagtenburg (1970) has proposed a simple nondestructive technique for estimating herbage biomass by placing a rigid weighted sheet on a grass surface and measuring the average distance to the ground after some settling period. Phillips and Clarks (1971) have developed this further by developing a weighted disc "meter" by attaching the weighted metal plate to a shaft carried in a vertical guide mounted on a tripod. Accurate measurements of the compressed height were reported after a predetermined settling time. The same device has been further evaluated by Powell (1974) for various grazing situations.

The basis for the weighted disc method is that a relationship exists between the compressed vegetation height and the vegetation biomass. Both Phillips and Clark (1971) and Powell (1974) reported different calibration relationships for different times of the year. These were attributed to differences in dry matter percentages and species composition with season.

REMOTE SENSING TECHNIQUES

Remote sensing techniques involve the measurement of reflected spectral radiance which results from the interaction between the plant canopy and the incident solar spectral irradiance. These measurements can be made from any altitude above the grassland or pasture surface (1 m, 10,000 m, 1000 km) depending upon the remote sensing system in question (ground-based, aircraft, and satellite, respectively). Remote sensing of forage biomass will be discussed here from a ground-based perspective although the same principle(s) apply to aircraft and satellite systems as well.

The various canopy and other variables affecting or controlling the plant canopy - irradiance interaction have been investigated and will not be reviewed in this article. Interested readers are referred to Colwell (1974), Smith and Oliver (1974), Tucker (1977a,b), Duggin (1977), Kriebel (1978), and Kimes et al. (1979) for technical discussion of these causative phenomena.

Spectral estimation of forage biomass generally uses two wavelength regions: The red (0.60-0.70 μm) and the near infrared (IR) (0.75 - 1.00 μm). The specific wavelengths used often vary slightly between different workers but the same two regions are generally used. It should be noted that spectral methods of biomass estimation are sensitive to the amount of green leaf area or green leaf biomass present. The selection of the (0.60 - 0.70 μm) region corresponds to the in vivo red region of chlorophyll absorption and is inversely related to the chlorophyll density. The 0.75 - 1.00 μm region corresponds to the region of the spectrum where reflectance is proportional to the green leaf density. Linear combinations of these two wavelength regions thus contain information related to the chlorophyll - green leaf interaction.

Use of these two bands for making nondestructive plant canopy inferences is facilitated by the fact that the two bands in question are closely situated to each other in the electromagnetic spectrum. If the atmospheric water absorption bands, situated at ~0.76 - 0.78 and ~0.92 - 0.98 μm are avoided, atmospheric transmission and absorption characteristics are similar for these two spectral regions. This enables the use of simple band ratios or other linear combinations to be used to compensate for different solar flux intensities.

Linear combinations of red and photographic infrared spectral data have been used in a variety of different vegetational situations. Jordan (1969) reported that the radiance ratio of 0.800/0.675 μm, when sensed on the forest floor, was highly correlated to tropical forest leaf area index. Pearson and Miller (1972), Colwell (1974), Rouse et al. (1974), Deering et al. (1975), Maxwell (1976), McNaughton (1976), Pearson et al. (1976), Deering (1978) and Tucker et al. (1980a) have all reported the use of these data for estimating forage biomass. Colwell et al. (1977), Tucker et al. (1980b), and Pinter et al. (1979) have reported using these data to predict winter wheat grain yield. Tucker et al (1980a and b) have reported these data to be sensitive to plant vigor and drought stress in alfalfa and winter wheat, respectively. Thompson and Wehmanen (1979), using a related technique, have reported good agreement between Landsat satellite data and drought stress. Wiegand et al. (1979) have reported the use of these data for evapotranspiration and crop growth modeling. Holben et al. (1980) have reported that red and photographic infrared spectral data were most highly correlated to soybean green leaf area index or green leaf biomass. Tucker et al. (1980c) have reported red and photographic infrared spectral data, when integrated over the growing season, where highly related to winter wheat total dry matter accumulation.

The evidence has accumulated from a variety of cover types that red and photographic infrared spectral data are highly sensitive to the projected green leaf area index or projected green leaf biomass (Deering, 1978; Tucker, 1978 and 1979; Holben et al., 1980). Their utility in assessing standing crop biomass is thus tied to the relationship of the green leaf area index to the standing crop biomass for the cover type in question. It therefore follows that these spectral data are not always related to standing crop biomass at a given point in time.

Several environmental conditions must be controlled when using the spectral method. Measurements are usually made in direct sunlight within 1 to 3 hours of solar noon. Failure to observe this procedure results in the introduction of additional variability resulting from solar zenith angle effects (Duggin, 1977; Kreibel, 1978; Kimes et al., 1979). Solar zenith angle effects upon the canopy reflectance are due in part to different projected leaf area indices and different proportions of shadows cast in the plant canopy with sun angle (Kimes et al., 1979).

To date, most spectral measurements of vegetation have been made in direct sunlight. The effect of overcast conditions upon plant canopy reflectance is not sufficiently understood at present but different spectral reflectances result from direct sunlight vis-a-vis overcast conditions (Kreibel, 1979). This means that a calibration procedure developed for direct sunlight conditions will not work under overcast conditions. The current inability of the same spectral calibration to hold under varying illumination conditions is a major limitation of this technique. Spectral techniques are not seriously affected by moisture on the vegetation, by wet or damp soil, or by uneven microtopography. Field instruments are relatively inexpensive (~$2000 US) and have applications for laboratory green/brown cut herbage percentage determinations (Tucker, 1980).

The spectral method is thus greatly restricted by irradiational circumstances. Where measurements can be made under similar conditions, the results have been encouraging. The greatest strength of the spectral method is the fact that it can be used to monitor large areas from aircraft and satellite platforms. In this fashion, large areas can be measured in a matter of seconds. However, this is not applicable at this time to the majority of ground-based nondestructive biomass estimation requirements. A significant amount of research is continuing which should determine if the many sources of measurement variation can be compensated for in small-scale ground-based applications of this technique.

COMPARISONS BETWEEN THE VARIOUS METHODS

Among the techniques reviewed in this paper β-attenuation suffers in that it has not been systematically evaluated in different field situations. The existing in situ evidence, while interesting, is too limited and inconclusive for substantive β-attenuation evaluation. In addition, the difficulties associated with using radioisotopes are drawbacks to this technique.

Capacitance meters, the weighted disc, and spectral methods all suffer to varying degrees from calibration problems. Capacitance meters measure the electrical conductivity of herbage material which is largely related to the amount of water present in, on, or near the vegetation. Environmental conditions such as dew, relative surface soil dampness, and humidity introduce significant sources of variation into the capacitance-biomass relationship as do variable amounts of standing dead vegetation. Calibration relationships are species composition specific.

The weighted disc method likewise suffers from differing calibration relations with season. This has been attributed to varying dry matter percentages and species composition changes (Powell, 1974). It follows that any variables which alter the vegetation compression-biomass relationship will degrade this technique accordingly. Furthermore, the weighted disc method has not been evaluated

on a variety of grazing situations. The suitability of this technique to heterogeneous pastures or rangelands appears limited.

Spectral methods similarly suffer from varying calibration relationships. Variables which affect the species composition, projected green leaf area, the proportion of shadows, and the spectral quality of the incoming irradiance (clouds, sun angle, etc.) all require different calibration relationships. Where these factors can be controlled, the spectral technique can be applied from the ground, aircraft, and/or satellite as so desired. However, environmental conditions greatly restrict the present application of this technique in many locations (due to overcast sky conditions).

The visual method for assessing herbage biomass, while admittedly unsatisfactory in many respects, still appears to be the most reliable small scale ground-based method under a wide range of species composition, dry matter percentages, and environmental circumstances.

CONCLUSION

The choice of which nondestructive biomass estimation method to use depends upon the particular grazing situation. For large area surveys, the spectral method has been shown to work well and allows for synoptic coverage of large areas from aircraft and/or satellite platforms. For smaller scale ground-based biomass estimation, the spectral method, capacitance meter, and weighted disc all suffer to varying degrees from species composition, dry matter percentages, amount of standing dead vegetation, and environmental factors. The spectral method, while applicable from aircraft and spacecraft platforms, can suffer substantially from environmental variability in small scale applications. Capacitance meters suffer from variable humidity, dew, and other water related sources of variability. The weighted disc technique has been reported to work well in some seasons and not at all in others.

The choice of which nondestructive biomass estimation method to use depends on the specific research application in question. In many localized ground-based situations, unfortunately, a reliable nondestructive substitute for the visual estimation method coupled with traditional clipping may not exist.

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